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Objective Indicators of Organizational Performance at Nuclear Power Plants

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Prepared by J. Olson, R. N. Osborn, D. H. Jackson, R. Shikiar/BHARC

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Pacific Northwest Laboratory

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

This report summarizes research conducted under the sponsorship of the NRC, on the development and validation of organizational performance measures at operating nuclear power plants. Publicly available data, including measures from Licensee Event Reports, operating and outage data, and violations data, are used to predict penultimate measures of plant safety. Penultimate measures of safety include potentially significant events, overexposures and near overexposures, and several radiological release measures. The 1981 and 1982 performance measures are used in correlation and regression analyses to predict performance on the penultimate safety measures in 1982 and 1983.

Many of the plant performance measures are consistently predictive of the frequency of potentially significant events. No strong, consistent predictors emerge for exposures or liquid radiological releases. Several performance measures are consistent predictors of gaseous releases. The regression analyses indicate that the predictors do not tend to combine in consistent, multivariate patterns, and controls for plant age, size, type, region, and fuel cycle stage do not substantially affect the results.

The analysis concludes that existing performance data do appear to be predictive of some aspects of plant safety performance. The report recommends that more reliable, summary performance measures be created by combining several of the performance measures tested in the current analysis.

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EXECUTIVE SUMMARY

INTRODUCTION

The purpose of this report is to summarize research conducted under the sponsorship of the Nuclear Regulatory Commission (NRC), on the development and validation of organizational performance measures at operating nuclear power plants, which appear to be stable predictors of plant safety performance. More specifically, the report acquaints the reader with the organizational model used to derive the candidate performance measures, the statistical analysis of these measures, and the nature of their relationships to plant safety.

This work has been performed under the project "Objective Safety Assessment for Utility and Nuclear Power Station Organization and Management," FIN B2457, Office of Nuclear Regulatory Research. This project addresses the need for the development of objective indicators of safety-related performance for use in the assessment of management and organization identified in Revision 1 (Section 6.1) of NUREG-0985, U.S. Nuclear Regulatory Commission Human Factors Program Plan. The need for objective safety performance measures derives from two sources. The first is with the increasing concern over the role of management and organization in assuring plant safety, as stimulated by recent problems encountered in the construction and reliable operation of several plants. The second is that the NRC currently has no set of performance indicators that are both widely accepted and validated in the sense that their relationship to safety has been objectively documented.

The analysis contained in this report is a significant step in the development of such indicators, in that it examines the relationship of three of the NRC's major sources of information on power plant performance (i.e., Licensee Event Reports, operating and outage data contained in NUREG-0020, and violations data) to a set of measures which at least partially assess plant safety.

BACKGROUND

An earlier report, NUREG/CR-3215, has identified a number of ways that organizational factors can be expected to determine plant safety performance. The approach is summarized in Figure 1.

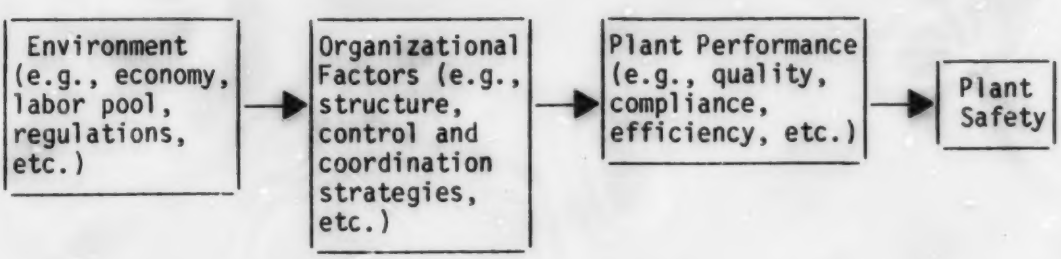
Environment (e.g., economy, labor pool, regulations, etc.)
Organizational Factors (e.g., structure, control and coordination strategies, etc.)
Plant Performance (e.g., quality, compliance, efficiency, etc.)
Plant Safety

Figure 1. A Model of Organizational Effects on Plant Safety

An effective organization for safety is one that mobilizes human performance to assure that quality, compliance, efficiency, and innovation goals are met, so that systems and components assure the safe operation of the plant. To assess the adequacy of any particular organizational approach, however, it is necessary to have valid and reliable measures of human and hardware performance. Valid measures are those which are both logically and demonstrably related to safety. Once valid and reliable performance measures are developed, the task of identifying the most effective organizational approaches can begin. The analysis in this report examines the relationship between certain performance measures and certain measures of plant safety.

THE APPROACH

A major obstacle to the development of valid and reliable performance measures is that direct measures of plant safety (e.g., serious accidents, significant overexposures and massive releases) do not exist. This is due to the generally good safety performance of the industry to date. Consequently, statistical analyses are impossible that demonstrate the relationship between performance measures and direct measures of safety. Instead, it is necessary to identify conditions which either dramatically increase the likelihood of direct safety effects (e.g., substantial degradation in plant safety systems or excessive challenges to those systems) or which are similar to, but less serious instances of the direct measures of safety (e.g., exposures and releases which approach or exceed regulatory limits). As outlined in Figure 2, these penultimate safety measures can be used in place of the direct or ultimate safety measures in an attempt to validate the performance measures. The relationships between the performance measures and the penultimate measures of safety, then, constitute the focus of this report.

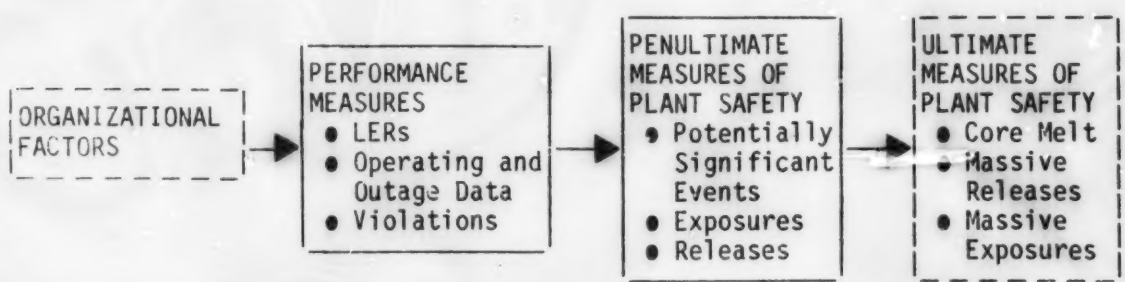

Figure 2. Scope of the Current Analysis

The penultimate safety measures included in the analysis are:

- The number of potentially significant events per year (i.e., the 40 to 50 events which experts have judged as having potentially high safety significance).
- The number of radiological exposures approaching or exceeding regulatory limits.

- The number of abnormal (unplanned) radiological releases.
- The percent of technical specification limits on radiological releases attained by a plant.

The plant performance measures used included:

- The number of human error related Licensee Event Reports (LERs)
- The number of LERs with significant effects on system status
- The number of scrams
- The number of forced outages
- The number of scheduled outages
- The number of major violations
- The number of minor violations

Data were analyzed for 66 plants for the years 1981, 1982, and 1983. Correlations between each of the plant performance measures (predictors) and each of the penultimate safety measures in subsequent years were calculated. Plant performance measures which successfully predicted the penultimate safety measures in both 1982 and 1983 were judged to be validated. Regression analysis was used to determine if consistent combinations of performance measures could be identified that predict plant performance on the penultimate safety measures. Regression analysis was also used to institute statistical controls for plant type, size, age, region, and stage of the fuel cycle.

RESULTS

The results of the correlational analysis were as follows:

- Five performance measures (i.e., human error and system effect LERs, scrams, forced outages, and major violations) were predictive of potentially significant events.
- A number of performance measures, including scrams, forced outages, and human error LERs, were predictive of gaseous radiological releases.
- No performance measures were consistently predictive of exposures.
- No performance measures were consistently predictive of liquid radiological releases.

The results of the regression analyses indicated the following:

- Consistent combinations of predictors did not tend to emerge from the analyses.

- The addition of controls for plant characteristics did not substantially affect the results.

- Additional analyses which (1) add currently missing data, (2) explore ways to combine performance measures into more reliable summary measures, and (3) more precisely model the statistical interactions between the control variables and the performance measures could lead to even stronger, more consistent results.

CONCLUSIONS

The analysis lends considerable support to the position that measures derived from LERs, operating and outage data, and violations data are useful in assessing Licensee performance, and in predicting subsequent performance on the penultimate safety measures. While not able to predict subsequent exposure rates, a number of the measures were consistently predictive of the frequency of potentially significant events and certain of the radiological release measures. A number of additions to and refinements of the analysis were identified including the addition of missing data, the construction of summary indicators from the individual performance measures, the testing for statistical interactions between the predictors and the control variables, and the examination of monthly or quarterly lags in the relationships. Such extensions to the analysis contained in this report would further clarify the relationship between existing plant performance data and safety. The result would likely be a useful tool to combine with and enhance the NRC's other mechanisms for evaluating the safety performance of plants.

ACKNOWLEDGMENTS

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1. INTRODUCTION

The purpose of this report is to summarize research conducted under the sponsorship of the Nuclear Regulatory Commission (NRC) on the development and validation of organizational performance measures which appear to be stable predictors of plant safety performance at operating nuclear power plants (NPPs). More specifically, the report acquaints the reader with the organizational model used to derive the candidate performance measures, the statistical analysis of these measures, and the nature of their relationships to plant safety. This analysis represents an initial attempt by the NRC to derive and validate, on an empirical basis and using existing performance data, objective performance measures that could be used in NRC evaluations of operating plants.

This work has been performed under the project "Objective Safety Assessment for Utility and Nuclear Power Station Organization and Management," FIN B2457, Office of Nuclear Regulatory Research. The analysis contained in this report comprises one part of a wider program investigating the relationship between plant management and organization and safety. A detailed discussion of the wider program can be found in NUREG/CR-3215. Guiding the wider program is the assumption that organizational factors, including management, play central roles in NPP safety. As discussed in more detail below, the organizational factors help determine how effectively the human and the hardware elements of the plant operate to assure plant safety. However, not all organizational approaches can be expected to be equally effective. In order to determine which approach is most effective, it is necessary to compare the different organizational approaches to valid, objective measures of plant safety performance to see which approach results in better performance. The analysis in this report attempts to develop such measures, by examining the relationship between publicly available measures of plant performance and aspects of plant safety.

This report is divided into three sections, in addition to this Introduction.

Section 2 provides background on the project and a rationale for the analysis contained in this report. In this section, the logic behind the analysis to be performed is discussed. This includes a discussion of approaches to assessing plant safety, of the role of organizational issues in assuring plant safety, and of the previous efforts carried out within the wider program.

Section 3 provides a more detailed description of the analysis strategy, including the identification of variables to be used in the analysis. Section 3 also reports on the findings of the analysis.

Section 4 provides a discussion of the results and conclusions.

A technical Appendix is provided which includes additional statistical information on the measures used in the analysis.

2.0 BACKGROUND AND RATIONALE

The purpose of this section is to provide the rationale for the analysis contained in this report. This includes the presentation of a model relating organizational factors to safety and an identification of the part that the current analysis plays in that model. A brief discussion of some experiences from the nuclear industry showing the importance of organizational factors to plant performance is also given. Finally, the general approach to assessing safety performance used in this analysis is outlined.

2.1 The Role of Organizational Factors in Plant Safety

2.1.1 Elements of the Model

The analysis contained in this report is part of a larger analytic effort spanning several projects and oriented toward a comprehensive assessment of the role of organizational factors in NPP safety performance. Figure 2.1, which is adapted from NUREG/CR-3215, summarizes this model.

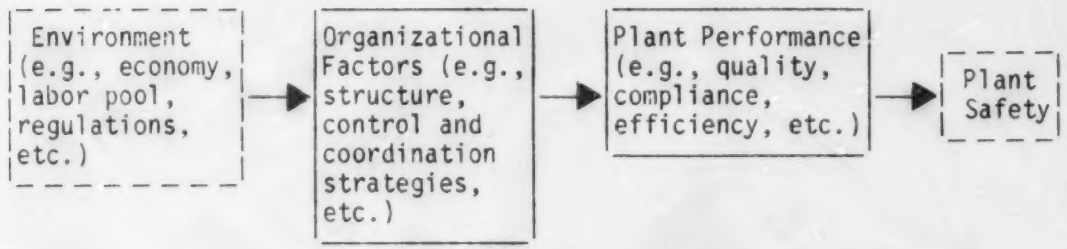
Environment (e.g., economy, labor pool, regulations, etc.)
Organizational Factors (e.g., structure, control and coordination strategies, etc.)
Plant Performance (e.g., quality, compliance, efficiency, etc.)
Plant Safety

Figure 2.1. A Model of Organizational Effects on Plant Safety

Several types of analysis are implied by this model. First, organizational factors, such as organizational structure, control and coordination strategies, etc., are seen as being influenced by the environment within which the utility operates. Second, these same factors are seen as being important determinants of plant performance on such dimensions as quality and compliance. Finally, the way the plant performs on these dimensions is seen as determining the plant's safety performance in the long run.

The model was originally developed under a project begun in Fiscal Year 1982 (NRC FIN B2457). In combination with an Office of Nuclear Reactor Regulation project (NRC FIN B2360) an initial survey of the performance data in the nuclear industry was conducted and available data were combined into multiple indicators which reflected most of the plant performance dimensions identified in NUREG/CR-3215 as being relevant to plant safety (e.g., quality, compliance, efficiency). Under NRC FIN B2360, measures of selected organizational factors were developed and compared to the indicators. This analysis is represented by the arrow linking the two middle boxes in Figure 2.1. The analysis showed that certain organizational forms tended to be related to better plant performance than were others. There were two important limitations to

this initial analysis, however. First, only a limited number of the organizational factors likely to influence plant performance were available from existing information sources. Thus, a comprehensive analysis of the influence of organizational factors on plant performance was not possible. The second limitation was that the performance indicators used had only a hypothetical (i.e., untested) relationship to plant safety.

Consequently, in addition to the need to more completely assess the relationships between organizational factors and the performance measures, the model also requires an assessment of the relationship between the performance measures and plant safety.

The need for this type of analysis has been recognized by the NRC. Specifically, Revision 1 (Section 6.1) of NUREG-0985, U.S. Nuclear Regulatory Commission Human Factors Program Plan, identifies the need for the development of objective indicators of safety-related performance for use in the assessment of organizational factors. This need results from the important roles that organizational factors are believed to play in determining a plant's level of safety performance, and from the fact that there currently are no widely accepted, statistically validated plant safety performance measures in the industry. Should such indicators become available, the NRC and industry would be in a position to (a) monitor the safety performance of the industry and individual plants, and (b) determine whether various approaches to and initiatives in the organizational area have the desired effects on plant safety performance.

The analysis described in this report constitutes a partial test of the part of the model relating plant performance measures to safety.

2.1.2 Some Evidence on the Importance of Organizational Factors

Organizational factors have both a logical and an observable relationship to plant performance and, therefore, to safety. This subsection starts by briefly outlining how organizational factors are logically related to plant performance and safety. Following this, several findings from the nuclear industry will be briefly discussed which are related to major events, and which demonstrate the relevance of organizational factors to plant safety.

The performance of the human element of the plant, which is itself crucial for the continued proper performance of systems and components, has no particular inherent reliability. Rather, acceptable levels of human performance must be continually created through the application of a wide range of resources such as skill, training, decision aids, motivation, coordination, and the like. The organization is essential in assuring that the needed resources are available and are expended to assure the ongoing proper performance of the human and hardware elements of the plant. While not the main focus of this report, a brief review of the role of organizational factors in assuring plant safety is in order, since it helps legitimate the performance assessment approach to safety taken here.

When the workers in the NPPs do their jobs, they are in need of a wide range of resources in order to be effective. These resources include such things as motivation, equipment and tools, information, skills, and direction. For example, to adequately maintain a safety-grade component, a maintenance worker needs to know how and when to perform maintenance. The worker must have replacement parts and tools, and the worker's efforts must be coordinated with others to assure that plant safety status is not adversely affected by having the component out of service during maintenance. The worker depends upon the organization to make all these resources available.

How does the organization achieve this goal? Briefly put, the organization is itself, a collection of resources for defining, controlling, and coordinating work. These resources may be grouped into the following categories:

1. The organization of work: This category refers to the assignment of tasks to positions or work units within the organization, and the formal reporting and coordinating relationships among positions and units.

2. Policies and Procedures: This category refers to formal statements about how the work is to be conducted both generally (policies) and specifically, or step-by-step (procedures).

3. Staffing: This category refers to the selection, training, motivating, appraising, and allocating of the human element in the plant.

4. External relations: This category refers to how the organization takes advantage of resources outside the organization (e.g., vendors, industry performance data) to provide the information and direction that help the workers do their jobs.

To fully assess the impact of the organization on performance, each of these dimensions would have to be considered. Clearly, when the organization is not providing adequate resources in these areas, the performance of the plant will suffer. This can easily be seen in a number of the more significant events in the nuclear industry in recent years.

The published material on the role of management in NPP safety predates the Three Mile Island-2 (TMI-2) incident. The Advisory Committee on Reactor Safeguards (ACRS) report NUREG-0572 asserted that up to 50% of all incidents were the result of human failures. These failures, in turn, were brought on by inadequacies in organizational resources such as procedures and properly trained staff.

With the TMI-2 event, an increased amount of attention has been paid to the role of organizational factors. The Rogovin Report (NUREG/CR-1250), for example, pointed to inadequacies in organizational structure and management qualifications and training of TMI-2 management staff (Rogovin, 1980, p. 920). The Kemeny Commission made a similar claim, stating that

General Public Utilities did not pay adequate attention to management qualifications and attitudes (Kemeny, 1979, p. 46). Both reports identified weaknesses in the utility's system for incorporating lessons learned from the industry--another organizational weakness. More recently, organizational problems have been identified as among the primary determinants of poor quality assurance performance during design and construction of NPPs (NUREG-1055). Thus, organizational factors may be a key to understanding plant performance. An approach to assessing the safety significance of existing plant performance measures will be discussed next.

2.2 A Performance Assessment Approach

Few topics in the nuclear industry are as constantly and hotly debated as that of how to assess the safety performance of plants. One reason for the lack of agreement on measuring and evaluating safety performance is that direct measures of safety are not usually available. This is due to the fact that plants rarely experience serious accidents, and even more rarely perform in a manner which directly degrades public health and safety. Because direct effects on public health and safety, heretofore, have been minor, assessors of plant performance have usually taken an indirect approach: the measuring of safety risks. This indirect approach addresses the question of the probability of a serious accident with direct effects on public health and safety. Plants with low accident probabilities are judged safer than plants with higher accident probabilities--even though, heretofore, both types of plants have had insignificant, direct effects on public health and safety.

There are several probabilistic approaches to NPP safety performance. Probabilistic Risk Assessment (PRA) is one dominant approach that attempts to predict the probability of plant failure from the combined probabilities of component failures within a set of causal chains. Another basic probabilistic approach is concerned less with assessing specific causal chains leading to accidents, and more with assessing the actual performance of components (both human and hardware) believed to be necessary in some general way for the safe operations of plants. This approach can be called the performance assessment approach. Systematic Assessments of Licensee Performance (SALP), Institute of Nuclear Power Operations (INPO) Plant Evaluations, and most analyses of operating and outage data, and Licensee Event Report (LER) data all fall into this latter category.

To some extent, all such analyses have a substantial subjective component, since the exact relationships between the performance dimensions used and plant safety have not been systematically analyzed. Thus, a deficiency in the performance assessment approach is that the performance dimensions that are normally measured have, at best, only a hypothetical relationship to plant safety. For example, the performance data collected by the NRC (e.g., LERs, forced outages, scrams, violations, etc.) have logical, but untested relationships to plant safety. It has not yet been empirically demonstrated that such phenomena degrade public health and safety. To demonstrate that high numbers of forced outages, scrams, violations, etc., degrade public health and safety, it would be necessary to measure the

relationship between the frequency of these events and the number or scale of injuries and deaths resulting from NPP operation. Since these ultimate indicators of plant safety performance (e.g., injuries and deaths) do not exist, such a test is impossible. However, it is possible to measure a class of penultimate events, which are conditions that are similar to, but less serious than the ultimate measures. If existing performance measures can predict the penultimate measures consistently, their continued use in evaluating plants will be based on objective evidence as to their validity. If not, the use of existing performance data for regulatory purposes will be called into serious question.

The approach taken here in the development of objective measures of plant safety performance is outlined in Figure 2.2, and involves an analysis of the relationship between major sources of currently available plant performance data and penultimate measures of plant safety (as illustrated by the boxes with solid lines). Penultimate measures of plant safety refer to conditions which are less severe manifestations of conditions which would have direct effects on public health. Such measures include events which seriously degrade the plant's ability to operate safely (e.g., substantial degradation in plant safety systems or excessive challenges to those systems), and the exposures and releases which approach or exceed regulatory limits. A more detailed rationale for the selection of these measures can be found in section 3.2.1.

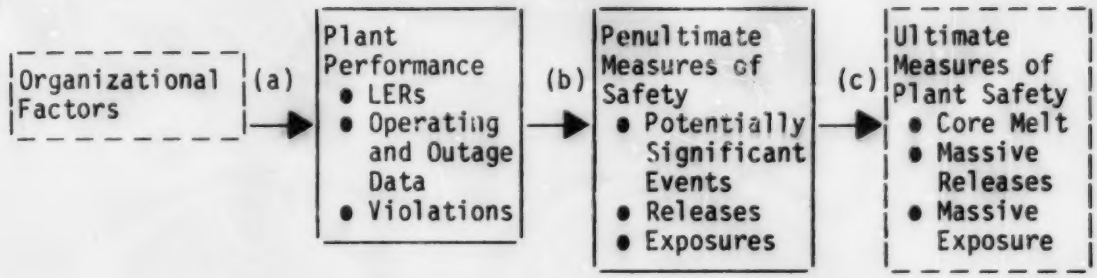

Figure 2.2. Scope of the Current Analysis

The arrow labeled (a) is a topic for future analysis. The arrow labeled (b) is subject to test with available data and forms the basis of the analysis in this report. Specifically, publicly available plant performance data were tested to determine if they could consistently predict subsequent performance of the penultimate measures of plant safety. Data for the industry for 1981 through 1983 were used. Arrow (c) is not testable, since data are not available on ultimate safety measures. The reasonableness of the analysis, therefore, rests on the assumption that the penultimate measures are only less serious manifestations of, or potential precursors to, the ultimate measures of safety--and that by inference, those conditions which were predictive of the penultimate measures would also be predictive of the ultimate safety measures. If systematic, stable relationships exist between the plant performance measures and the penultimate measures of safety, considerably more confidence would be warranted in the ability of the available data to validly assess the safety performance of NPPs. The next section describes such an analysis.

3. ANALYSIS

This section outlines the analytical approach to be used, identifies the specific measures employed, and reports on the findings of the analysis. Additional detail on the measures and their statistical properties may be found in the Appendix.

3.1 Analytical Approach

The specific analysis strategy employed here consisted of two major steps. The first step is identify plant performance and penultimate safety measures from available data. In the following section, the measures are defined, rationales are given for their inclusion, a brief discussion of the construction of the measures from existing data and their basic statistical properties are identified.

The second step is to conduct a statistical analysis of the relationships between each of the plant performance measures and each of the penultimate safety measures. This entails calculating correlations between the plant performance measures in one year and the penultimate safety measures in subsequent years. Both one year, and two year lags have been considered, since there is no empirical evidence identifying a single, best lag-interval. Plant performance measures which were significantly related to the penultimate safety measures in both 1982 and 1983 were judged as more valid indicators of plant safety than those that were not. In addition to the correlational analysis, the "validated" indicators have been combined into multiple regression equations to determine if multivariate performance models could be constructured that were consistent predictors across years for specific penultimate safety measure. Finally, a set of statistical controls have been applied to these equations to determine if the observed relationships can be enhanced or explained by considering plant characteristics such as reactor type, age, size, and region.

The analysis was conducted using data on the 66 plants that were operating (i.e., not in long regulatory or administrative shutdown) from the beginning of 1981 through 1983.

3.2 Description of the Measures

This section identifies the measures used in the analysis and provides rationales for their selection.

3.2.1 Penultimate Safety Measures

Three types of penultimate safety measures were selected: potentially significant events, radiological exposure, and radiological releases. Each of these types represent different aspects of risks to safety due to NPP operation, and will be discussed in turn. In general, however, the selection of these measures was guided by two criteria: that data be available from public sources, and that the measures have credibility as penultimate safety measures, as indicated by regulations or by their use in the industry.

The first penultimate safety performance measure selected was the number of potentially significant events. Data for this measure were obtained from the Oakridge National Laboratory (ORNL) maintained Sequence-Coded LER data base. Because LERs are filed on a self report basis by the utilities, there has long been concern that the frequency as well as the severity of events were underestimated, improperly coded, and/or unreliable. As a result, under the new uniform Sequence Code and Search system employed by ORNL, the cause and effect codes were independently assigned by ORNL engineers based on their reading of the event narrative. The potentially significant events employed in the analysis were LERs that the ORNL reviewers felt represented major threats to the safety of the plant or its personnel. Examples included the discovery of leaking and seriously degraded steam generator tubes, significant cracking in welds with potentially important safety consequences, significant uncontrolled releases due to component failures, severe feedwater leaks during events, and the like. There were approximately 50 such events per year identified within the industry, thus constituting a special class of serious events. A comparison of the types of events defined as potentially significant by ORNL to the types of events defined as significant by the Institute of Nuclear Power Operations (INPO) and the NRC's Office for the Analysis and Evaluation of Operational Data (AEOD) showed considerable overlap in the definitions. Thus, potentially significant events as defined by ORNL were included as a penultimate safety measure.

The data on radiological exposures used in this analysis were drawn from the NRC's publication Occupational Radiation Exposure at Commercial Nuclear Power Reactors (NUREG-0713). This source provided information on the number of persons exposed to radiation per level of exposure, and the occupational breakdowns of plant personnel exposed at various levels. The data are reported on an annual basis.

Because radiological exposures can be due to essential plant activities (e.g., maintenance and refueling), not all exposures constitute decrements to plant safety. Thus, it was judged inappropriate to use the plant's total MANREM exposure level as a penultimate safety measure. (A MANREM is a dose of one REM for a particular individual.) Instead, it was judged more appropriate to focus on the exposures at the upper end of the distribution of exposures when comparing plants.

Two variables were constructed to compare the upper end of the observed exposure level distribution across plants. The first variable measured whether or not there were any exposures at a given plant in excess of 5 MANREMs per year. Depending on the exposure history of a worker, 5 MANREMs can constitute an overexposure. Because there are so few workers experiencing this level of exposure, the distribution of workers exposed at greater than 5 MANREMs was highly skewed across the plants. To make the distribution suitable for statistical analysis, therefore, the measure had to be calculated as a dummy variable, with a value of zero if there were no exposures greater than 5 MANREMs at a plant and a value of 1.0 if there were any exposures greater than 5 MANREMs at a plant.

The choice of this variable as a penultimate safety measure was credible on several bases. First, depending on the exposure history of the

individual, a level of 5 MANREMs per year is recognized in the Code of Federal Regulations (10 CFR 20) as constituting an overexposure. Thus, this level approximated the boundary of safeness for worker exposures. This has been recognized by industry as well as the NRC, in that INPO included the number of workers exposed at 5 MANREMs or greater per year as one of its safety performance indicators (INPO, 1985).

The second variable measured the number of personnel at a given plant who received whole body doses of 4 MANREMs per year or more. The selection of this measure was based on two factors. First, the distribution of this variable was not as highly skewed as the previous measure. This allowed plants to be compared as to the number of workers with this exposure level rather than whether any workers had this exposure level. Second, workers with 4 MANREMs or greater are workers with a reasonable risk of exceeding the 5 MANREM per year limit on their next exposure. Thus, for many practical purposes, they are workers who have reached their exposure limits.

The data used to construct measures of liquid and gaseous radiological releases were prepared for the NRC by the Brookhaven National Laboratory (BNL) and were based on semi-annual utility submissions as required by the plants' technical specifications. (See NUREG/CR-2907 for a description of these data.) Data were obtained from BNL for both liquid and gaseous releases as well as the number of abnormal (unplanned) releases. For liquid releases, the types of radionuclides released fell into three general categories: fission and activation products, Tritium, and dissolved and entrained gases. For gaseous releases, data for four categories were obtained: fission and activation gases, Iodine-131 (I-131), particulates, and Tritium gas. For each of these categories, BNL provided the total volume released, the average release rate for the reporting period, and the percentage of the technical specification limit attained.

As with radiological exposures, radiological releases may have been due to either normal or poor operational performance. In addition, the amount of the release could differ across plants due to variations in plant siting characteristics as reflected in the technical specification limits for a given plant. As a result, the percentages of technical specification limits for the seven categories of radionuclides released were selected as the preferred release measures, since these figures were, in effect, standardized by plant specific considerations. Though most plants stayed within technical specification limits, a number were observed exceeding the limits for some categories in any given year.

In addition to the standardized amount of material released, measures of abnormal releases were also included in the analysis. The number of gaseous and liquid abnormal releases were counted for each plant, for each year. These constituted uncontrolled or unplanned releases of radioactive material to the environment, and thus indicated the plant's relative ability to contain the radioactive material.

3.2.2 Plant Performance Measures

Three sources of plant performance data were selected for this analysis: regulatory noncompliances, plant operating and outage data, and LERs. The sources were selected because they were publicly available and widely used to assess NPP performance. Each of these represented different aspects of plant performance which were hypothesized to increase the probability that the plants would experience poorer performance on the penultimate safety measures. Seven plant performance measures were constructed from these three data sources to serve as predictors of the penultimate safety measures. These measures were the same or similar to those frequently used in other assessments of plant performance (e.g., SALP, INPO). A previous review of existing data sources and a previous attempts to construct safety performance measures from existing data indicated that these types of measures are reasonable summary measures of the performance data contained in the three sources (NUREG/CR-3215; NUREG/CR-3737; NUREG/CR-4281). These measures generally reflect aspects of quality and compliance in performance. The scope of the current analysis, however, did not allow the combination of measures in a multiple indicator approach, as was done successfully in earlier reports (NUREG/CR-3215; NUREG/CR-3737).

Data for regulatory noncompliances were obtained from the NRC's 766 file. The 766 file data contained the number and type of compliances cited by the NRC's Inspection and Enforcement staff. The noncompliance data were reported by the degree of severity of the deviation from NRC regulations, with the most severe level of deviation coded as level 1 and the least severe deviation coded as level 5. (Prior to the second quarter of 1982, the NRC used six levels.)

Two plant performance measures were computed from the 766 file data: a count of major violations and a count of minor violations. Since violations of level 1 and 2 are extremely rare in the industry, it was not possible to analyze each severity level separately. Instead, it was necessary to collapse the violations into two severity levels. Major violations were defined as all violations in levels 1 through 3, inclusive. Levels 4, 5, and 6 were aggregated into a minor violations measure.

Operating and outage data were obtained from the NRC's monthly publications on licensed operating reactors (NUREG-0020). Information on electrical generation, availability, types of outages, method of shutdown, hours of shutdown, reason for shutdown, and the component system in which the problem generated are reported. Measures taken from NUREG-0020 for this analysis include the total number of scheduled outages, the total number of forced outages (including complete shutdowns and power reductions in excess of 20%), and the total number of scrams.

Two LER-based performance measures were included in the analysis. The first pertained to the total number of LERs with human error components. Using the sequence coding system, a human error LER was defined as any LER with a human error as a contributing cause. This measure was used because

it allowed for an assessment of the performance of the human element in the plant.

A frequent criticism of LERs is that they include a large number of essentially trivial events with no or little apparent safety significance. This fact was recognized by the NRC when, in 1984, it redefined what constituted reportable events. The redefinition resulted in an approximately 50% reduction in LERs filed. Because the current analysis used pre-1984 data, it was judged necessary to eliminate as many of the trivial events from the LER counts as possible. Consequently, a second measure was defined that referred to the total number of LERs with "system effects." This category referred to events which are associated with one or more of the following: manual, automatic, and unintentional scrams, required or unintentional engineered safety features (ESF) actuations, long forced outages, and natural circulation problems. This definition resulted in a fairly restrictive set of nontrivial LERs, with about 200 in the industry per year. Future analyses, based on post-1983 data, can more reasonably employ counts of total LERs.

3.2.3 Control Variables

In addition to the plant performance and penultimate safety measures, several control variables were used in the multivariate analysis. The control variables were considered for two reasons. First, it was possible that any observed relationships between plant performance and penultimate safety measures were spurious; that they were actually due to the influence of a third factor such as plant age or type. Entering the appropriate control variables into an equation simultaneously with the plant performance measures allowed for an assessment of this possibility.

Second, it was also possible that the relationships between the plant performance and penultimate safety measures were suppressed or hidden by the effects of the control variables. This constitutes a special case of nonlinearity in the relationships between the predictors and the penultimate measures. In such cases, the use of correlation and regression analysis would tend to under estimate the size of the relationships. While it was not been possible within the scope of this project to systematically examine nonlinearity in the relationships, some aspects of nonlinearity can be assessed by entering statistical controls on the relationships.

The control variables used in this analysis were those identified in earlier reports (NUREG/CR-3215; NUREG/CR-3737) as having potentially significant effects on the performance measures and, therefore, on the relationships between the performance measures and the penultimate safety measures. These included the following:

Reactor type: Coded as one if the reactor is a Boiling Water Reactor (BWR), and zero if the reactor is a Pressurized Water Reactor (PWR).

Reactor size: Coded as the designed capacity of net megawatts of electricity produced per year (MWe).

Region: Four regions equivalent to NRC regions I, II, III, and regions IV and V combined (due to the small number of cases) were coded as follows:

Northeast = 1 if in the Northeast; zero, otherwise.
Midwest = 1 if in the Midwest; zero, otherwise.
South = 1 if in the South; zero, otherwise.
West = 1 if in the West or Southwest; zero otherwise.

Age: Coded as the number of months operational prior to January 1, 1984.

In addition to these variables, a measure was calculated which was the percent of each year (1981, 1982, and 1983) that the plant was down for refueling. Many of the plant performance measures (e.g., forced outages, scrams, system effect LERs) were unlikely to occur during refueling outages. Therefore, it was necessary to control for the extent to which the plant was "at risk" of experiencing these events in a given year. The percent of the year spent in refueling provided such a control. This measure was derived from NUREG-0020.

3.3 The Sample

While the study's ideal was to structure the data set along a quarterly basis for time series analysis, the variation of reporting periods for the different data sources did not make this possible. This was a potentially significant limitation, particularly if the effects of the performance measures on the penultimate safety measures tend to emerge in less than a year's time. The yearly reporting of exposures meant that all data had to be aggregated to the year level.

There was also some variation across the data sources in the unit of analysis. Some data were coded with the unit of analysis as the site (e.g., exposure data), other data were coded with the plant as the unit of analysis, while a third set mixed the two. Where the data were reported with the site or facility as the unit of analysis, the individual plants at the site were assigned an equal portion of the site's figures.

An added complication with the release data was the substantial number of missing cases. For the liquid and gaseous release data, it was decided that if any quarterly data were missing, then the entire year was coded as missing for the measure in question. This was necessary in that it was impossible to determine from existing information whether the missing data resulted from different reporting requirements, the fact that no material was released, or that some material was released but not reported. This approach resulted in fewer than 20 cases for some yearly counts of Tritium gas.

For abnormal releases, however, it was decided that if no data were reported for a given quarter then the appropriate value for that quarter was likely to be zero. This assumption was warranted given the low average number of abnormal releases in the industry per year (i.e. one or

less). Therefore, it was decided to treat missing data as a zero if only one quarter out of four had missing data. Using this approach, the number of valid cases for abnormal releases increased to an average of thirty. As a check for bias introduced by this approach, a Chi-Square test was run between plant type, age, and size and the distribution of missing cases. The results indicated that there was no bias in terms of the distribution of missing cases across plant characteristics.

Data were collected for the 66 plants operating from 1981 through 1983. This represented nearly all of the 72 licensed operating reactors at the beginning of 1981. A few plants experiencing long, regulatory or administrative shutdowns (e.g., TMI-1 and TMI-2) were not included. The number of plants included in each part of the analysis, however, varied due to missing data for some variables.

The sample was comprised of approximately two-thirds PWRs and one-third BWRs. The average net megawatts per year (MWe) for the sample was 752. The average age of the plants was approximately 95 months at the beginning of 1984. The regional breakdowns were 29% in the Northeast, 32% in the Midwest, 33% in the South, and 6% in the West. The plants were down for refueling 16% of the year in 1981, 17% of the year in 1982, and 23% of the year in 1983.

3.4 Descriptive Statistics

For the interested reader, descriptive statistics for all of the variables in the analysis can be found in the Appendix, along with a detailed discussion of each variable. The tables in the Appendix provide a reference for the reader as to the average frequency of each event (reflected in the means), the degree of variation (reflected in the standard deviation), and the degree of departure from normality in the distribution of the variables (reflected in the skewness). This last point requires additional explanation.

The statistical techniques used in the analysis assume that the measures are approximately normally distributed about their means. This means that the distributions generally take on a bell shape. Skewness refers to the extent to which the distributions are lopsided, with more cases on one side of the mean than another or, stated another way, some cases further from the mean on one side than the other. As Tables A.1, A.2, and A.3 indicate, many of the variables are quite skewed, thus violating the assumptions of the statistical techniques used.

To determine whether the skewness in the variables invalidated the results reported in the next sections, the highly skewed variables were subjected to log transformations. This had the effect of drawing extreme values toward the mean and making the distributions more closely approximate normality. The analyses were then conducted with the logged variables and the results compared to those for the nonlogged variables. Since the differences were trivial, it was decided that skewness was not a major problem and the results with the nonlogged measures were reported here.

3.5 Results

This section presents the results of the analysis.

3.5.1 Correlational Analysis

The results of the correlational analysis relating the predictor variables to the proxy safety measures can be found in Tables 3.1, 3.2, 3.3 and 3.4. In discussing the results, the primary focus is on the cross year correlations, since they reflect the ability of the plant performance measures to predict subsequent performance on the penultimate safety measures.

To summarize the correlational analysis, the following basic points can be made:

1. Five variables were predictive of either two or all of the three cross-year correlations for potentially significant events.

2. No variable systematically predicted performance on either of the exposure variables, though major and minor violations were predictive in two of the three cross-year correlations.

3. No variable systematically predicted performance on liquid releases or the number of unplanned liquid releases.

4. There were several systematic predictors for unplanned gaseous releases, as well as two of the four categories of gaseous releases.

Based on these findings, there appeared to be considerable benefit to be derived from using existing plant performance data to assess plant safety performance. A more detailed discussion of the findings follows.

Potentially Significant Events: Table 3.1 contains the correlations between the plant performance measures and potentially significant events. Two variables were predictive of all three cross-year correlations: 1981 to 1982, 1982 to 1983, and 1981 to 1983. These measures are the number of forced outages, and the number of human error LERs. In addition, three other measures were predictive of the two one year lag relationships: 1981 to 1982 and 1982 to 1983. These were the number of scrams, the number of LERs with system effects, and the number of major violations. Scheduled outages and minor violations were not generally predictive of subsequent potentially significant events.

Radiological Exposures: Table 3.1 contains the correlations between the plant performance measures and the exposure measures. No measures consistently predicted exposure levels. For the Exposures $\geq$ 4 MANREMs measure, 1982 scrams, forced outages and LERs with system effects predicted exposure levels in 1983. However, these were the only significant relations in the predicted direction. For Exposures $\geq$ 5 MANREMs, major and minor violations in 1981 and 1982 were predictive of

TABLE 3.1

CORRELATIONS OF EXPOSURES AND POTENTIALLY SIGNIFICANT EVENTS
WITH PLANT PERFORMANCE MEASURES

		NUMBER OF EXPOSURES GREATER THAN 4 MAN/REMS		PRESENCE OF EXPOSURES GREATER THAN 5 MAN/REMS		POTENTIALLY SIGNIFICANT EVENTS	
PLANT PERFORMANCE MEASURES		1982	1983	1982	1983	1982	1983
1. Number of Scrams	1981	-.03	-.04	.01	.09	.25**	.12
	1982		.24**		.17*		.36#
2. Number of Scheduled Outages	1981	.14	.12	-.07	.14	.17*	.15
	1982		.15		.06		.11
3. Number of Forced Outages	1981	-.11	-.12	-.09	-.02	.29***	.23**
	1982		.17*		.13		.34***
4. Number of System Effect LERs	1981	.10	-.04	.21**	.13	.19*	.02
	1982		.20*		.02		.46#
5. Number of Human Error LERs	1981	-.01	.08	.10	-.00	.30***	.21**
	1982		-.10		-.13		.37#
6. Number of Minor Violations	1981	-.09	.16	-.07	.23**	-.01	.11
	1982		.06		.25**		.22**
7. Number of Major Violations	1981	-.16*	-.01	-.06	.24**	.26**	.11
	1982		.13		.30***		.34***

* = $p \geq .1$
** = $p \geq .05$
*** = $p \geq .01$
\# = $p \geq .001$
Correlations based on 65 plants.

TABLE 3.2

CORRELATIONS OF PERCENT OF TECHNICAL SPECIFICATION LIMITS FOR LIQUID RELEASES WITH PLANT PERFORMANCE MEASURES

PLANT PERFORMANCE MEASURES		FISSION & ACTIVATION 1982	FISSION & ACTIVATION 1983	TRITIUM 1982	TRITIUM 1983	ENTRAINED GASES 1982	ENTRAINED GASES 1983
1. Number of Scrams	1981	-.01	-.02	-.24*	-.03	.13	.13
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		.12		.40***		.35**
			(40)		(35)		(25)
2. Number of Scheduled Outages	1981	-.07	.06	-.13	-.04	.24	.17
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		.08		-.15		-.16
			(40)		(35)		(25)
3. Number of Forced Outages	1981	.08	.19	-.20	-.07	.13	.11
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		.13		+.09		.13
			(40)		(35)		(25)
4. Number of System Effect LERs	1981	-.08	-.15	.15	.14	-.07	-.07
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		-.01		.21		-.18
			(40)		(35)		(25)
5. Number of Human Error LERs	1981	.09	.04	-.11	.28**	.07	.08
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		.04		.05		-.02
			(40)		(35)		(25)
6. Number of Minor Violations	1981	-.10	-.08	-.06	.48***	.12	.04
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		.08		.19		-.07
			(40)		(35)		(25)
7. Number of Major Violations	1981	-.03	-.05	-.11	.12	-.17	-.17
		(49)	(40)	(35)	(35)	(24)	(25)
	1982		.23*		-.10		-.12
			(40)		(35)		(25)

* = $p \geq .1$
** = $p \geq .05$
*** = $p \geq .01$

TABLE 3.3

CORRELATIONS OF PERCENT OF TECHNICAL SPECIFICATION LIMITS FOR GASEOUS RELEASES WITH PLANT PERFORMANCE MEASURES

PLANT PERFORMANCE MEASURES		FISSION & ACTIVATION 1982	FISSION & ACTIVATION 1983	IODINE - 131 1982	IODINE - 131 1993	PARTICULATES 1982	PARTICULATES 1983	TRITIUM GAS 1982	TRITIUM GAS 1983
1. Number of Scrams	1981	-.22*	.16*	.20	.19	.22*	.23*	.39*	.32*
		(42)	(45)	(35)	(40)	(32)	(37)	(17)	(18)
	1982		.22		.25*		.24*		.19
			(45)		(40)		(37)		(18)
2. Number of Scheduled Outages	1981	.17	-.06	.00	-.14	.01	.01	.79#	.74#
		(42)	(45)	(35)	(40)	(37)	(37)	(17)	(18)
	1982		-.11		-.14		-.05		.75#
			(45)		(40)		(37)		(18)
3. Number of Forced Outages	1981	-.14	.08	.12	.06	.04	.07	.71#	.67#
		(42)	(45)	(35)	(40)	(37)	(37)	(17)	(18)
	1982		.07		-.01		.04		.75#
			(45)		(40)		(37)		(18)
4. Number of System Effects LERs	1981	-.15	.15	.22	.17	.17	.18	-.24	-.25
		(42)	(45)	(35)	(40)	(37)	(37)	(17)	(18)
	1982		.30**		.24*		.32**		.34*
			(45)		(40)		(37)		(18)
5. Number of Human Error LERs	1981	-.14	.22*	.37**	.09	.16	.31**	.45**	.47**
		(42)	(45)	(35)	(40)	(37)	(37)	(17)	(18)
	1982		.47#		.45***		.57#		.38*
			(45)		(40)		(37)		(18)
6. Number of Minor Violations	1981	-.17	.07	.12	.03	.05	.09	.17	.28
		(42)	(45)	(35)	(40)	(37)	(37)	(17)	(18)
	1982		.22*		.25*		.30**		.07
			(45)		(40)		(37)		(18)
7. Number of Major Violations	1981	-.13	-.13	-.09	-.04	-.13	-.06	-.08	.25
		(42)	(45)	(35)	(40)	(37)	(37)	(17)	(18)
	1982		.47#		.49#		.65*		-.04
			(45)		(40)		(37)		(18)

*p $\geq$ .1
**p $\geq$ .05
***p $\geq$ .01
#p $\geq$ .001
Numbers in parentheses are the number of cases.

TABLE 3.4

CORRELATIONS OF LIQUID AND GASEOUS ABNORMAL RELEASES WITH PLANT PERFORMANCE MEASURES

PLANT PERFORMANCE MEASURES		NUMBER OF LIQUID ABNORMAL RELEASES 1982	NUMBER OF LIQUID ABNORMAL RELEASES 1983	NUMBER OF GASEOUS ABNORMAL RELEASES 1982	NUMBER OF GASEOUS ABNORMAL RELEASES 1983
1. Number of Scrams	1981	-.05 (30)	.10 (31)	.36** (30)	.34** (31)
	1982		.22 (31)		.34** (31)
2. Number of Scheduled Outages	1981	-.05 (30)	-.18 (31)	.55# (30)	.62# (31)
	1982		.28* (31)		.03 (31)
3. Number of Forced Outages	1981	-.07 (30)	-.07 (31)	.48*** (30)	.49*** (31)
	1983		.07 (31)		.60# (31)
4. Number of System Effect LERs	1981	.13 (30)	.00 (31)	.19 (30)	.21 (31)
	1982		.01 (31)		.02 (31)
5. Number of Human Error LERs	1981	.38** (30)	.10 (31)	.05 (30)	.06 (31)
	1982		-.07 (31)		.14 (31)
6. Number of Minor Violations	1981	.44*** (30)	-.13 (31)	.40** (30)	.45 (31)
	1982		-.21 (31)		.23 (31)
7. Number of Major Violations	1981	-.04 (30)	.12 (31)	.10 (30)	.02 (31)
	1982		-.08 (31)		.03 (31)

* $p \geq .1$
** $p \geq .05$
*** $p \geq .01$
\# $p \geq .001$
Numbers in parentheses are the number of cases.

1983 exposures. The lack of consistency in relationships across the three years, however, suggests that the performance measures cannot serve as valid and reliable predictors of radiological exposures in their present form.

Radiological Releases: Tables 3.2, 3.3, and 3.4 contain the correlations between the plant performance measures and the release measures. The relationship of the performance measures to the radiological release measures is complex. For liquid releases (Table 3.2), no measure consistently predicts. This is true for the percent of Technical Specification limits attained for each of the categories of release, as well as the number of abnormal releases (Table 3.4).

The results were more positive for gaseous releases (Table 3.3). For fission and activation particles, and I-131, only the number of human error related LERs was predictive of releases, and this only for the 1982 and 1983 relationship. However, for particulates, scrams were predictive for all three cross-year correlations, and human error related LERs were significant for both the 1981 to 1983 and the 1982 to 1983 correlations. For Tritium gas, the results were even stronger, with the numbers of forced and scheduled outages and human error related LERs being predictive of all three cross-year correlations. In addition, the number of scrams in 1981 was related to Tritium releases in both 1982 and 1983. Finally, both forced outages and scrams were consistently related to the number of unplanned gaseous releases (Table 3.4), with the cross year correlations being significant in every case. The number of scheduled outages and the number of minor violations in 1981 were related to the number of unplanned releases in both 1982 and 1983.

Thus, whereas no stable predictive relationships emerged for radiological exposures and liquid releases, the results were much more encouraging for potentially significant events and gaseous releases. With some oversimplification, the number of scrams, the number of forced outages, and the number of human-error related LERs were the most consistent predictors.

3.5.2 Multivariate Analysis

The previous subsection identified the relationships between the individual performance measures and the penultimate safety measures. Four of the penultimate safety measures (e.g., potentially significant events, percent technical specification releases for particulates and tritium, and the number of abnormal gaseous releases) were consistently predicted by one or more of the performance measures across the three years of data in the analysis. This subsection explores whether multivariate models can be constructed from the significant bivariate measures to predict the four penultimate measures for which consistent bivariate relationships existed.

One major advantage to taking a multivariate approach is the likely increase in predictive power. If combinations of predictors can be found which are the same across the three years, the predictive powers of the individual performance measures can be added into a more powerful

multivariate equation. Another reason for estimating multivariate models is that this allows for an assessment of the relative strength of the individual predictors. A final reason for the multivariate approach is that it allows for an understanding of the effects of one predictor while simultaneously controlling for the other predictors. To explore these issues, the plant performance measures that were significantly related to the penultimate safety measures in two or more of the cross year correlations have been combined into multiple regression equations. These equations are given in Tables 3.5, 3.6, and 3.7.

Table 3.5 gives the regressions for the 1982 penultimate safety measures with the 1981 performance measures. Table 3.6 gives the regressions for the 1983 penultimate safety measures with the 1982 plant performance measures. Table 3.7 gives the regressions for the 1983 penultimate safety measures with the 1981 plant performance measures. In these tables, the coefficients are the standardized regression coefficients. The R^2 values constitute the proportion of variation in each of the penultimate safety measures accounted for by the linear combination of performance measures. Only performance measures that were determined by the correlational analysis to be consistently predictive of the penultimate safety measures were included in the regression equations.

In terms of potentially significant events, no consistent multivariate model emerges from the regressions. The number of major violations is predictive in two of three cases, but no other measures are significant when combined in the regression equations. The proportion of explained variation ranges from 34% to an insignificant 17%. This pattern of results suggests that the various performance measures which were significantly related to the frequency of potentially significant events in the correlational analysis are related in much the same way. Therefore, they do not add much predictive power to the equation beyond that which they share in common. Rather than invalidating the results of the correlational analysis, however, this finding strongly suggests that the various performance measures be combined into a summary scale or index. The likely result is a performance measure with greater reliability and, therefore, greater predictive power relative to the penultimate safety measure. Unfortunately, it was not possible to pursue this approach within the scope of this project.

No consistent multivariate model emerges for the percent of technical specification limits of particulates. The regression equation is significant in only one of the three equations (Table 3.6). In this case, the number of human error LERs is the only significant predictor. This pattern again illustrates the need to consider combining the predictors into summary scales.

The results for the percent of technical specification limits for tritium are somewhat stronger, though with a very important caveat. This caveat is that the analysis is based on too few cases to instill confidence that the results will hold true for the population of plants. The proportion of explained variation for all three equations is over 80%, denoting high predictive power. Both the number of scheduled and the number of forced

TABLE 3.5

REGRESSIONS OF 1982 PENULTIMATE SAFETY MEASURES WITH
1981 PLANT PERFORMANCE MEASURES

PLANT PERFORMANCE MEASURES	PENULTIMATE SAFETY MEASURES			
	POTENTIALLY SIGNIFICANT EVENTS	% TECH SPEC RELEASE: PARTICULATES	% TECH SPEC RELEASE: TRITIUM	GASEOUS ABNORMAL RELEASES
Number of Scrams	.08	.19	-.21	.04
Number of Scheduled Outages			.60***	.40***
Number of Forced Outages	.13		.58***	.27
Number of System Effect LERs	-.04			
Number of Human Error LERS	.20	.10	.17	
Number of Minor Violations				.15
Number of Major Violations	.21*			
R^2	.17**	.06	.89***	.42***
Adjusted R^2	.10	.00	.85	.33
N	66	37	17	30

* = $p \leq .1$
** = $p \leq .05$
*** = $p \leq .01$

TABLE 3.6

REGRESSIONS OF 1983 PENULTIMATE SAFETY MEASURES WITH
1982 PLANT PERFORMANCE MEASURES

PLANT PERFORMANCE MEASURES	PENULTIMATE SAFETY MEASURES			
	POTENTIALLY SIGNIFICANT EVENTS	% TECH SPEC RELEASE: PARTICULATES	% TECH SPEC RELEASE: TRITIUM	GASEOUS ABNORMAL RELEASES
Number of Scrams	.13	.12	-.35**	-.16
Number of Scheduled Outages			.48***	-.34**
Number of Forced Outages	.12		.69***	.84***
Number of System Effect LERs	.32**			
Number of Human Error LERS	.04	.55***	.19*	
Number of Minor Violations				.10
Number of Major Violations	.26**			
R^2	.34***	.34***	.88***	.47***
Adjusted R^2	.29	.30	.85**	.39
N	.66	37	18	31

* = $p \leq .1$
** = $p \leq .05$
*** = $p \leq .01$

TABLE 3.7

REGRESSIONS OF 1983 PENULTIMATE SAFETY MEASURES WITH
1981 PLANT PERFORMANCE MEASURES

PLANT PERFORMANCE MEASURES	PENULTIMATE SAFETY MEASURES			
	POTENTIALLY SIGNIFICANT EVENTS	% TECH SPEC RELEASE: PARTICULATES	% TECH SPEC RELEASE: TRITIUM	GASEOUS ABNORMAL RELEASES
Number of Scrams	-.04	.14	-.29	-.01
Number of Scheduled Outages			.56***	.45***
Number of Forced Outages	.21		.59***	.28
Number of System Effect LERs	-.15			
Number of Human Error LERS	.21	.26	.22	
Number of Minor Violations				.20
Number of Major Violations	.08			
R^2	.09	.11	.82***	.50***
Adjusted R^2	.02	.06	.76	.42
N	66	37	18	31

* = $p \leq .1$
** = $p \leq .05$
*** = $p \leq .01$

outages are consistent predictors across the three equations. However, due to the small number of cases, and the relatively large number of variables in the equations, the results should be taken as suggestive, rather than conclusive.

The results for the number of gaseous abnormal releases do not suggest consistent multivariate models. For the equations in Tables 3.8 and 3.10 more scheduled outages are associated with more abnormal releases. In Table 3.9, however, more scheduled outages are associated with fewer abnormal releases. This pattern of findings illustrates the importance of considering the simultaneous effects of the performance measures, in that the reversal of the direction of effects in Table 3.6 can probably be attributed to the very large effect of the number of forced outages on abnormal releases. When controlling for the number of forced outages, the incremental effect of the number of scheduled outages is in the opposite direction than is its overall effect. This suggests that most scheduled outages have effects that are similar to the effects of forced outages, while a smaller number do not.

The following summarizes the results of the regression analyses:

In general, consistent multivariate models of the effects of the plant performance measures on the penultimate safety measures did not emerge.

The pattern of results indicate that some of the performance measures should be combined into potentially more reliable and powerful summary measures.

Data are necessary for a larger number of plants in order to have greater confidence in some of the results.

Instituting simultaneous controls through multiple regression illustrates that certain of the performance measures, most noticeably the number of scheduled outages, are related to the penultimate safety measures in complex ways.

The regression results do not invalidate the correlational results. Rather, they illustrate the potential for the development of more powerful multivariate models by more systematically investigating strategies for combining measures, investigating nonlinearity, and adding cases to the data base.

3.5.3 Multivariate Analysis with Controls

The final step in the analysis was to implement controls for plant type, region, reactor size, age, and percent of the year spent in refueling. For the most part, the implementation of the controls did not materially affect the regression results. The results of these analyses may be found in Tables 3.8, 3.9, and 3.10.

For potentially significant events, no performance measures and none of the control variables were statistically significant. Accordingly, the

TABLE 3.8

REGRESSIONS OF 1982 PENULTIMATE SAFETY MEASURES WITH 1981 PLANT PERFORMANCE MEASURES AND CONTROL VARIABLES

PLANT PERFORMANCE MEASURES	PENULTIMATE SAFETY MEASURES			
	POTENTIALLY SIGNIFICANT EVENTS	% TECH SPEC RELEASE: PARTICULATES	% TECH SPEC RELEASE: TRITIUM	GASEOUS ABNORMAL RELEASES
Number of Scrams	.02	.13	-.14	.13
Number of Scheduled Outages			.52***	.83***
Number of Forced Outages	.11		.60***	.42***
Number of System Effect LERs	-.03			
Number of Human Error LERS	.15	.04	.23***	
Number of Minor Violations				.27**
Number of Major Violations	.17			
BWR/PWR	.02	.47***	.17	-.76***
Northeast	-.24	-.11	-.13	.19*
Midwest	-.08	-.23	.00	.51***
West	.00	-.04	-.03	.13
MWe	.13	-.03	-.13	.05
Age	.01	-.03	.12	.30**
% Year in Refueling	-.05	-.14	.00	.31***
R^2	.22	.29	.97***	.88***
Adjusted R^2	.04	.06	.91	.81
N	66	37	17	30

* = $p \leq .1$
** = $p \leq .05$
*** = $p \leq .01$

TABLE 3.9

REGRESSIONS OF 1983 PENULTIMATE SAFETY MEASURES WITH
1982 PLANT PERFORMANCE MEASURES AND CONTROL VARIABLES

	PENULTIMATE SAFETY MEASURES			
PLANT PERFORMANCE MEASURES	POTENTIALLY SIGNIFICANT EVENTS	% TECH SPEC RELEASE: PARTICULATES	% TECH SPEC RELEASE: TRITIUM	GASEOUS ABNORMAL RELEASES
Number of Scrams	.24	.15	-.33*	-.20
Number of Scheduled Outages			.46***	-.27
Number of Forced Outages	.22		.67***	.96***
Number of System Effect LERs	.34**			
Number of Human Error LERS	.06	.51***	.11	
Number of Minor Violations				.27
Number of Major Violations	.27*			
BWR/PWR	.09	.37**	.07	-.30
Northeast	.32**	-.19	-.12	.15
Midwest	.18	-.15	.00	.18
West	.15	.00	-.05	.13
MWe	-.16	-.15	.02	-.10
Age	-.02	.00	-.06	.04
% Year in Refueling	.06	.04	.12	-.04
R^2	.43***	.51***	.92***	.56*
Adjusted R^2	.29	.35	.77	.30
N	66	37	18	31

* = $p \leq .1$
** = $p \leq .05$
*** = $p \leq .01$

TABLE 3.10

REGRESSIONS OF 1983 PENULTIMATE SAFETY MEASURES WITH
1981 PLANT PERFORMANCE MEASURES AND CONTROL VARIABLES

PLANT PERFORMANCE MEASURES	PENULTIMATE SAFETY MEASURES			
	POTENTIALLY SIGNIFICANT EVENTS	% TECH SPEC RELEASE: PARTICULATES	% TECH SPEC RELEASE: TRITIUM	GASEOUS ABNORMAL RELEASES
Number of Scrams	.01	.01	-.26	.09
Number of Scheduled Outages			.52***	.89***
Number of Forced Outages	.17		.66***	.42***
Number of System Effect LERs	-.12			
Number of Human Error LERS	.22	.17	.21	
Number of Minor Violations				.31***
Number of Major Violations	.02			
BWR	.17	.45***	.05	-.76***
Northeast	.06	-.32	-.12	.23***
Midwest	-.07	-.26	.18	.44***
West	.00	-.09	-.02	.11
MWe	.02	-.06	.08	-.06
Age	.02	-.09	.08	.27***
% Year in Refueling	.17	-.26		.30***
R^2	.16	.40*	.88**	.93***
Adjusted R^2	.00	.20	.70	.89
N	66	37	18	31

* = $p \leq .1$
** = $p \leq .05$
*** = $p \leq .01$

R^2s for the equations were not significant. Again, these results indicated that the performance measures that were found to be significant at the correlational stage could probably be profitably combined into a summary measure. Further, this summary measure would likely be significant, even when controlling for plant characteristics.

For the percent of technical specification limits for particulates, the addition of the control variables did not significantly alter the effects of the performance measures: no performance measures were significant in the multivariate case. One control variable was significant. BWRs had significantly higher particulate releases than PWRs.

Because of the small number of cases, the results for Tritium are of very limited generalizability. None of the control variables were significant, although in the presence of the control variables, some significant changes were observed on the effects of Human Error LERs. In one case, the 1981 to 1982 relationship, the previously nonsignificant effect of Human Error LERs became significant. In another case, the 1982 to 1983 relationship, the previously significant effect of Human Error LERs became nonsignificant. In general, however, the implementation of controls did not have major effects on the results.

Finally, the results for gaseous abnormal releases provide an example of how controlling for the plant characteristics can clarify the relationship between the predictors and the penultimate measures of safety. In both the 1981 to 1982, and the 1981 to 1983 relationships, the addition of the controls increased the effects of certain variables to the point that they became significant. Specifically, in the 1981 to 1982 relationship, both the number of scheduled outages and the number of minor violations became significant predictors when the controls were added. For the 1981 to 1983 relationship, the addition of the controls increased the size of the effect of scheduled outages, and resulted in both the number of minor violations and the number of forced outages becoming significant. In the 1982 to 1983 relationship, the number of scheduled outages became nonsignificant.

A number of the control variables were also significant, with BWRs, Southern, younger plants, and plants with a lower than average time in refueling having fewer abnormal releases.

In general, the addition of the control variables did not substantially affect the relationships between the predictors and the penultimate safety measures. This fact indicates that these relationships were not primarily determined by basic design or other plant characteristics. Instead, the relationships may be due to how the plant is operated, indicating that improvements can be made in the predictor variables and thus, in some cases, the penultimate safety measures, beyond the limitations imposed by the plant characteristics. In the next section, a more complete discussion of the results will be undertaken.

4. SUMMARY AND CONCLUSIONS

This section provides a summary of the major findings of the analysis and draws conclusions based on them. This section also identifies limitations in the current analysis and strategies, which if incorporated into future analyses, may lead to even stronger and more useful findings.

The analysis summarized in this report draws upon the most frequently used plant performance data (operating and outage data, LER data, and violations data) to determine if measures derived from them can successfully predict plant performance on the penultimate safety measures. Penultimate measures of safety were defined as plant conditions (e.g., especially significant events, and releases and exposures at the high end of the observed distributions) which either substantially increased the probability of harm to the public, or approached or exceeded regulatory or industry safety standards.

Data for 66 plants operating between 1981 and 1983 were used in the analysis. The first stage of the analysis was to calculate correlations between the plant performance measures and the penultimate safety measures. Correlations were calculated for the relationships between 1981 plant performance measures and the 1982 and 1983 penultimate safety measures, and for the relationships between the 1982 plant performance measures and the 1983 penultimate safety measures. Plant performance measures that were consistently predictive of the penultimate safety measures in 1982 and 1983 were tentatively judged to be valid predictors of plant safety performance.

The second step in the analysis was to determine if multivariate combinations of predictors could be constructed from the significant univariate predictors. Multiple regression equations were estimated which used combinations of plant performance measures to predict the penultimate safety indicators. To partially explore the effects of differences in plant characteristics (e.g., plant age, size, type, etc.) a series of control variables were added to the regression equations.

The results of the analyses were mixed, although the overall results show considerable support for the position that existing performance data can be used to assess plant performance relative to some aspects of safety. Specifically, consistent predictors were found in the cases of potentially significant events, for particulates and tritium gas releases, and for abnormal gaseous releases. All three plant performance data sources contributed significant, stable predictors. None of the performance measures, however, were capable of predicting rates of personnel exposure, or liquid releases.

The results of the multiple regression analyses did not produce stable, consistent multivariate combinations of predictors. However, several important implications for the use of plant performance data emerged from the analysis. First, the regression results indicated that many of the plant performance measures seemed to be related to the penultimate safety measures in much the same way. Therefore, the possibility exists that there could be combined into more reliable summary measures through a

factor analytic approach. This was, in fact, one of the original goals of this project and consistent with the findings of earlier analyses (NUREG/CR-3215).

A second major finding is that the control variables (e.g., age, size, etc.) do not seem to play major roles in the determination of variation in the penultimate safety measures. Instead, the plant performance measures tend to be more highly predictive than the control variables. However, it may well be the case that the effects of the plant performance measures on the penultimate safety measures are different for different categories of the control variables. For example, separate analyses relating the plant performance measures to the radiological release variables for all BWRs and all PWRs may result in the discovery of more consistent and stable relationships. Again, it was not possible to pursue this line of analysis within the scope of this project.

A final analytic consideration for future analyses is to consider other than yearly summary data. It may well be the case that poor performance on the plant performance measures manifests itself in poor performance on the penultimate safety measures more quickly than that represented by a one or two year lag. To assess this possibility, monthly and quarterly causal lags should be considered.

The findings of this analysis are encouraging for the development of valid, reliable safety performance measures from publicly available data. While it was not possible to predict exposures or liquid releases, the analysis had considerable success in predicting potentially significant events and some aspects of gaseous releases. The extensions of the analysis recommended above could well serve to increase the ability of the plant performance measures to predict plant safety performance.

Finally, it is recommended that data on organizational factors be collected for inclusion in an analysis of the complete model outlined in Figure 2.1. By relating organizational factors to validated measures of plant safety performance, much could be learned about effective ways to organize nuclear power plants for safety.

REFERENCES

INPO. "Long Term Industry Goals." Attachment to correspondence from INPO to William J. Dircks, U.S. Nuclear Regulatory Commission, September 16, 1985. Atlanta, Georgia. U.S. NRC Public Document Room, Washington, D.C.

Kemeny, J. G. (Chair). The Need for a Change: The Legacy of TMI. Report of the President's Commission on the Accident at Three Mile Island. Washington, D.C. 1979.

NUREG-0020. Licensed Operating Reactors: Status Summary Report. U.S. Nuclear Regulatory Commission, Washington, D.C. (published monthly).

NUREG-0572. Review of Licensee Event Reports (1976-1978). Advisory Committee on Reactor Safeguards, U.S. Nuclear Regulatory Commission, Washington, D.C. 1979.

NUREG-0713. Occupational Radiation Exposure at Commercial Nuclear Power Reactors. U.S. Nuclear Regulatory Commission, Washington, D.C. (published yearly).

NUREG-1055. Improving Quality and Assurance of Quality in the Design and Construction of Nuclear Power Plants. Office of Inspection and Enforcement, U.S. Nuclear Regulatory Commission, Washington, D.C. 1984.

NUREG-1250. Three Mile Island: A Report to the Commissioners and to the Public, Volumes I and II. U.S. Nuclear Regulatory Commission. M. Rogovin, Director, Special Inquiry Group. 1980.

NUREG/CR-2907. Radioactive Materials Released from Nuclear Power Plants, Annual Report 1981. Prepared by Brookhaven National Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D.C. (published yearly).

NUREG/CR-3215. Organizational Analysis and Safety for Utilities with Nuclear Power Plants. Prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D.C. 1983.

NUREG/CR-3737. An Initial Empirical Analysis of Nuclear Power Plant Organization and Its Effect on Safety Performance. Prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D.C. 1984.

NUREG/CR-3905 LD. Sequence Coding and Search System for Licensee Event Reports. Prepared by Oakridge National Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D.C. 1984.

NUREG/CR-4281. An Empirical Analysis of Selected Nuclear Power Plant Maintenance Factors and Plant Safety. Prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D.C. 1985.

APPENDIX

This Appendix provides more detailed statistical information on the variables used in the analysis. Included is a discussion of the descriptive statistics for each variable.

DESCRIPTIVE STATISTICS

The descriptive statistics covered in this Appendix are the means, standard deviations, skewness, and the number of cases. These are reported for each variable used in the analysis. For most of the variables used in the analysis, the frequency distributions show that the mode (i.e., the most common occurrence) tends to be at the low end of the distribution. The skewness statistic's value in such circumstances will take a positive value and the larger the value, the greater the right-hand tail of the distribution will be due to a few extreme values. In general, if there is no skewness (i.e., the distribution is centered about the mean), the value of the skewness statistic will be zero. Similarly if most of the distribution is centered about a high value but there are several very small values, then the skewness statistic will be negative.

Altogether, there were 12 variables used as penultimate safety measures. These variables were observed over three time periods from 1981 to 1983. Table A.1 provides the summary statistics for each of the 12 penultimate safety measures for each year.

The indicator of potentially significant events was available for all 66 plants under investigation. The mean number of such events was .85 for 1981, .77 for 1982, and .85 for 1983. The standard deviations for these variables are 1.11 for 1981, .86 for 1982, and 1.03 for 1983. The distributions are slightly skewed to the right, indicating relatively few outlying cases.

Two variables for radiological exposures were used in the study. The first measure indicated whether or not there were any exposures at a plant that were greater than 5 MANREMs per year. Because this variable was calculated as a dichotomized variable, the summary statistics should be interpreted as percentages of the total data base. Data were available for 65 plants, with 26% reporting such exposures for 1981, 20% for 1982, and 19% for 1983. The second, the number of exposures greater than 4 MANREMs, measures the number of persons at a plant that were reported to have such high levels of MANREMs. The mean value across the 65 plants for which there were data shows a relatively low number of workers exposed at this level: 8.37 in 1981, 7.42 in 1982, and 8.87 in 1983. However, the standard deviations, as well as the skewness figures indicate that there is considerable variation about these mean values. The standard deviations for 1981 and 1983 are quite large indicating that for at least some plants, many workers received high exposures.

The release data contain substantial missing information. There are 49 valid cases for the fission and activation measures in 1981 but only 17 valid cases for Tritium gas measures in 1982. The variables listed in

TABLE A.1

DESCRIPTIVE STATISTICS FOR PENULTIMATE SAFETY MEASURES

VARIABLE	1981				1982				1983			
	$\bar{X}$	S	SKEW	N	$\bar{X}$	S	SKEW	N	$\bar{X}$	S	SKEW	N
Potentially Significant Events	.86	1.11	1.19	66	.77	.86	.92	66	.85	1.03	1.02	66
Number of Exposures Greater than 4 MAN/REMs	8.37	21.52	4.00	65	7.42	14.07	2.34	65	8.87	18.86	3.28	65
Any Exposure Greater than 5 MAN/REMs	.26	.44	1.11	65	.20	.40	1.54	65	.19	.39	1.67	65
% Technical Specification Limit of:[a]												
a. Fission & Activation Products	1.73	2.50	1.98	49	2.01	3.67	3.90	44	1.52	2.36	3.05	40
b. Tritium	1.05	2.60	3.28	40	1.12	2.48	2.70	35	.98	2.61	3.05	35
c. Entrained Gases	.13	.38	4.00	25	.25	.80	3.30	24	.26	.83	3.64	25
d. Fission & Activation	25.65	168.39	6.99	49	5.15	20.17	6.08	42	1.85	4.07	3.87	45
e. Iodine-131	1.07	1.821	2.23	42	.74	1.68	3.20	35	1.59	3.63	3.36	40
f. Particulates	1.07	1.96	2.28	42	1.11	3.10	3.16	37	1.12	3.60	3.95	37
g. Tritium Gas	.38	.72	2.18	20	1.52	4.59	3.66	17	1.63	3.79	2.91	18
Number of Abnormal Liquid Releases	.42	1.43	4.96	33	.30	.62	3.12	30	.19	.54	2.82	31
Number of Abnormal Gaseous Releases	2.06	4.92	3.46	33	1.20	4.06	4.96	30	.36	1.44	5.275	31

$\bar{X}$ = Mean

S = Standard Deviation

N = Number of Cases

[a] = The means for % of technical specification limits for each of the radionuclides constitute the average % of the limits achieved.

Table A.1 are the percentages of technical specification limits. Hence, the mean statistics for these variables should be read as percents. In general, the percentage of technical specification limits tend to be rather low for all years under consideration, except for the mean value of the gaseous fission and activation variable where the mean is 25.65% for 1981, and 5.15% for 1983. In both of these cases, the standard deviation and the skewness is also quite high indicating that the high mean is due to a few outlying cases. For the rest of the variables and years, the mean value ranges between .13% (n = 25) for entrained gases in 1981 to 2.01% (n = 44) for liquid fission and activation products in 1982. The distributional characteristics, like those for gaseous fission and activation products, are skewed to the right with relatively large standard deviations.

Like the percentage of technical specification variables, the number of cases and the frequency of abnormal releases (for both gases and liquids) were quite small. There were .42 unplanned liquid releases in 1981, .30 in 1982, and .19 in 1983, per plant. For unplanned gaseous releases, there were 2.06 in 1981, 1.20 in 1982, and .36 in 1983, per plant. For both types of abnormal releases, the size of the standard deviation relative to the mean is large indicating large variation in the frequency of these variables, especially for gaseous abnormal releases.

Seven variables were used as measures of plant performance. As with the penultimate safety measures, these seven variables were also observed over the 1981 to 1983 time interval. Table A.2 gives the descriptive statistics for these variables.

Two variables were used to measure the degree of regulatory noncompliance. The first variable, minor violations, measures the number of violations given to a particular plant that were in severity levels 4, 5, and 6. The second variable, major violations, measures the number of violations for a given plant in severity levels 1, 2, and 3. For minor violations, there was a mean of 22.06 in 1981, 16.39 in 1982, and 14.38 in 1983. For major violations, there was a mean of 1.70 in 1981, 1.09 in 1982, and 1.00 in 1983. For minor violations, the standard deviations are 11.01 for 1981, 8.85 for 1982, and 10.73 for 1983. Because the standard deviations for minor violations are smaller than their respective means, the distributions can be considered relatively tightly distributed about the mean. This is reflected also in the size of the skewness factor for the years 1981, and 1982 where the value is less than 1.0. For 1983, the distribution is more skewed and the standard deviation is larger relative to the mean than for 1981 and 1982. This indicates that there are a few outlying cases for 1983, or plants with significantly more minor violations than for the rest of the 66 plants under consideration. For major violations, the trend is reversed: the standard deviations are larger than the means indicating more dispersion in the distribution. This suggests that there is more variation across plants with respect to major violations and more outlying cases, which is also reflected in the size of the skewness statistic.

TABLE A.2

DESCRIPTIVE STATISTICS FOR PLANT PERFORMANCE MEASURES (PREDICTORS)

VARIABLE	1981				1982				1983			
	$\bar{X}$	S	SKEW	N	$\bar{X}$	S	SKEW	N	$\bar{X}$	S	SKEW	N
Number of Scrams	6.62	4.86	1.37	66	5.42	3.79	1.00	66	4.67	3.51	1.00	66
Number of Scheduled Outages	6.42	6.24	1.38	66	7.26	9.02	2.59	66	7.91	12.02	3.04	66
Number of Forced Outages	16.27	14.92	2.26	66	12.96	8.92	1.32	66	12.90	14.56	4.67	66
Number of System Effect LERs	3.12	2.73	1.01	66	2.67	2.51	1.07	66	2.39	2.35	.85	66
Number of Human Error LERs	15.62	10.46	.70	66	15.88	13.27	1.46	66	14.12	9.68	1.04	66
Number of Minor Violations	22.06	11.01	.93	66	16.39	8.85	.71	66	14.38	10.73	2.01	66
Number of Major Violations	1.70	2.42	1.76	66	1.09	1.54	2.10	66	1.00	1.39	2.48	66

$\bar{X}$ = Mean
S = Standard Deviation
N = Number of Cases

Three variables were derived from NUREG-0020: the total number of scrams, the total number of scheduled outages, and the total number of forced outages. There were averages of 6.62 scrams in 1981, 5.42 scrams in 1982, and 4.67 scrams in 1983. There were averages of 6.42 scheduled outages in 1981, 7.26 scheduled outages in 1982, and 7.91 scheduled outages in 1983. It should be noted that the distribution of scheduled outages becomes more dispersed and skewed to the right across time. This may be due to more plants requiring refueling (which is classified in NUREG-0020 as a scheduled outage) or that more scheduled maintenance outages are required over time. In either case, the periodicity of fuel cycles and the limitations of the data set (i.e., covering only three years) prevent a clear answer to this effect. For forced outages, the average number of outages for 1981 is 16.27 , 12.95 in 1982, and 12.80 for 1983. For both types of outages, the distribution is skewed to the right suggesting that there are outlying cases.

Two LER-based plant performance measures were used: System Effect and Human Error LERs. For System Effects LERs, the mean values were 3.12 LERs in 1981, 2.67 in 1982, and 2.39 in 1983. The distributions appear to be relatively skewed to the right with a moderate dispersion of observations about the mean. For the Human Error LERs, the mean number of occurrences over the three year period are larger than the system effect LERs: 15.62 in 1981, 15.88 in 1982, and 14.12 in 1983. The distributions are moderately skewed to the right with the distribution for 1981 approximating normality.

It appears to be the case that almost all of the plant performance and penultimate safety measures are improving over time (i.e. from 1981 to 1983). While this may, in fact, be the case, caution is advised in drawing this conclusion. In the first place, additional years of data should be considered before concluding that the data reflect a linear trend rather than a cycle. In the second place, these data also indicate an increasing rate of scheduled outages--a fact which could account for the decline in LERs, scrams, forced outages, and the like.

As noted above, there were numerous problems with the number of missing cases. These problems were generally contained in the release data. The Chi-Square tests run between observed and missing cases with reactor type, showed no significant bias in the reporting practices within the commercially operating power plant population. In general, a recalculation of the variables was able to increase the number of valid cases. The high degree of skewness in the data suggested that the general assumptions of linearity which underlie many of the statistical techniques employed here would be violated (i.e., the assumption of normal distributions). It was, therefore, determined that log transformations of many of the variables may be required. This means that the values for a given variable would be logged and this new variable would be used with the linear models employed in the analyses. Several log transformations were calculated for the penultimate safety measures and correlated with the plant performance measures. The general result was that there was no appreciable difference between the correlations for the logged and the nonlogged variables. Hence, it was decided that despite the skewness

among many of the variables, the linear model and its assumptions would be used.

Table A.3 provides the descriptive statistics for the control variables used in the analysis. These variables were discussed fully in the text.

TABLE A.3

DESCRIPTIVE STATISTICS FOR CONTROL VARIABLES

VARIABLE	$\bar{X}$	S	SKEW	N
Percent of Year Refueling:				
1981	16.13	13.33	.69	66
1982	18.66	17.99	.78	66
1983	22.72	20.69	1.21	66
Percent of Sample BWR	.36	.49	.58	66
Percent of Sample PWR	.64	.49	-.51	66
Net Megawatts	752.14	237.15	-.87	66
Percent of Sample in Northeast Region	.29	.46	.96	66
Percent of Sample in Midwest Region	.32	.47	.80	66
Percent of Sample in South Region	.33	.48	.72	66
Percent of Sample in West Region	.06	.24	3.77	66
Number of Months Operational Prior to January 1, 1984	94.78	41.86	.84	66

$\bar{X}$ = Mean
S = Standard Deviation
N = Number of Cases

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16 ABSTRACT (200 words or less)

This report summarizes research conducted under the sponsorship of the NRC, on the development and validation of organizational performance measures at operating nuclear power plants. Publicly available data, including measures from Licensee Event Reports, operating and outage data, and violations data, are used to predict penultimate measures of plant safety. Penultimate measures of safety include potentially significant events, overexposures and near overexposures, and several radiological release measures. The 1981 and 1982 performance measures are used in correlation and regression analyses to predict performance on the penultimate safety measures in 1982 and 1983. Many of the plant performance measures are consistently predictive of the frequency of potentially significant events. No strong, consistent predictors emerge for exposures or liquid radiological releases. Several performance measures are consistent predictors of gaseous releases. The regression analyses indicate that the predictors do not tend to combine in consistent, multivariate patterns, and controls for plant age, size, type, region, and fuel cycle stage do not substantially affect the results. The analysis concludes that existing performance data do appear to be predictive of some aspects of plant safety performance. The report recommends that more reliable, summary performance measures be created by combining several of the performance measures tested in the current analysis.

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